/

NASA TECHNICAL TRANSLATION NASA TT F-15,147

CALCULATION AND COMPARISON OF THE ECONOMICS OF ELECTROCHEMICAL FUEL CELLS

F. A. Pohl, J. Boehm and H. Carl

Translation of: "Berechnung und Vergleich der Wirtschaftlichkeit von elektrochemischen Brennstoffzellen," Wissenschaftliche Berichte AEG-Telefunken, Vol. 45, No. 3, 1972, pp 141-146

(NASA-TT-F-15147) CALCULATION AND COMPARISON OF THE ECONOMICS OF ELECTROCHEMICAL FUEL CELLS (Techtran Corp.) 17 p HC $3.00 CSCL 10A

N73-31991

Unclas

G3/03 18359

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 OCTOBER 1973

STANDARD TITLE PAGE

1. Report No. NASA TT F-15,147	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CALCULATION AND COMPARISON OF THE ECONOMICS OF ELECTROCHEMICAL FUEL CELLS		5. Report Date OCTOBER 1973
		6. Performing Organization Code
7. Author(s) F. A. Pohl, J. Boehm and H. Carl		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Techtran Corporation P.O. Box 729 Glen Burnie, Maryland 21061		11. Contract or Grant No. NASw-2485
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of: "Berechnung und Vergleich der Wirtschaftlichkeit von elektrochemischen Brennstoffzellen," Wiss. Ber. AEG-TELEFUNKEN, Vol. 45, No. 3, 1972, pp. 141-146. (A73-25346)

16. Abstract

This paper deals with the economic benefits to be derived from various types of electrochemical fuel cells. It is found that the tungsten carbide-carbon cell is most economic in the low temperature fuel cell range, and that high fuel costs are more significant than high investment costs.

17. Key Words (Selected by Author(s))	18. Distribution Statement
(See A73-25346	Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	16	

CALCULATION AND COMPARISON OF THE ECONOMICS OF ELECTROCHEMICAL FUEL CELLS[1]

F. A. Pohl, J. Boehm and H. Carl

Introduction and Summary

/141*

Electrochemical fuel cells transform the chemical energy of fuels directly into the electrical energy without any intermediate thermal or mechanical process and thus with no restrictions because of the Carnot cycle. Already at the end of the 19th century this led to expectations of higher economy and the beginning of a new age of energy transformation from this source of energy [1]. Nevertheless it was only in 1939 that Bacon [2] first took up the problem again and constructed a high pressure hydrogen-oxygen combustion cell on the basis of which the later fuel cell batteries for the Apollo space vehicles [3] were developed. In the last 20 years support of this and other fuel cell projects with state resources led in the United States to a considerable expansion and intensification of the research and developmental work in this area. In the meantime this work was again cut and to some extent completely interrupted because it was shown that the fuel cells developed for spaceflight and military purposes are not suitable for economic application. They are either constructed of expensive materials or require expensive fuels.

From the beginning in the Federal Republic of Germany fuel cell research had the goal of economic application in view and already at the beginning of the 1950s Justi [4] had set down 10 conditions for economically promising hydrogen-oxygen electrodes. The fact that the desired introduction of fuel cells has not yet come to pass today, in spite of great efforts, has a number of reasons with which we shall deal later in this journal [5]. Essentially these are the sensitivity of alkali fuel cells to carbon dioxide and thus to cheap,

[1]The work upon which this report is based was partially supported with resources from the Federal Ministry for Education in Science. The Federal Minister for Education in Science does not accept any responsibility for the correctness, the accuracy and the completeness of the data or for respect for the private rights of third parties.
*Number in the margin indicates pagination in the foreign text.

carbon-containing fuels, the necessity of using noble metal electrodes in fuel cells with acid electrolytes, and the sensitivity of metal catalysts to catalyst poisons.

The tungsten carbide-carbon fuel cell suggested by us [5] can be considerably improved in its performance and is technically so far advanced that forward looking deliberations on its economy and utility now seem appropriate.

This work will first treat the calculation of economy and will end by comparing several examples of the economy of various low temperature fuel cells with each other. A further work [6] is intended to consider the usefulness of the tungsten carbide-carbon fuel cell and a comparison with other energy sources. As the computations and comparisons show, the tungsten carbide-carbon fuel cell is more economical than other low temperature fuel cells.

1. Calculation of Energy Production Costs

A rather large number of various kinds of costs enter into the costs of energy production. These can be classified in 3 groups:

- financial expenditure and capital service,
- operation costs,
- direct costs of energy transformation.

An exact determination of energy production costs requires careful analyses of the individual cost components so that they can be grasped in a numerically exact manner. In the strict sense this is only possible if fuel cells are already in production and if fuel cell sets can be investigated in practical operation. In extrapolating from the developmental phase into the manufacturing or energy production phase only approximations are possible. In our considerations we have tried to use only data which corresponds to the state of technology or seem feasible today.

In assembling the costs within the above mentioned groups we must consider: /142

Financial Expenditure and Capital Service

Investment costs for the fuel cell set and possible buildings

Capital interest on investments in the fuel cell set including auxiliary devices and also building investments in rather large establishments

Amortization of set, machines and material

Amortization of developmental costs

Rent for real estate, buildings and installations

Insurance costs

<u>Operating Costs</u>

Salaries and wages for maintenance personnel

Maintenance costs

<u>Energy Transformation Costs</u>

Fuel costs

Transportation costs for fuel and containers (important in connection with field tanks)

Electrolyte costs

Material costs for converting and purifying gases

No arrangement of indices and symbols for the necessary concepts is known for mathematical comprehension and treatment of the cost components mentioned. Various and evidently arbitrary symbols are used in [7] to [9], but accepting them for our considerations does not appear sensible. Therefore we have chosen symbols which correspond best to the concepts used.

1.1. Financial Expenditure and Capital Service K_k

If we wish to transfer investments, interest and amortization to the cost of the power produced, the following relationship provides for the simplest case (and without regard to building costs or to the amortization of developmental costs):

$$K_K = \frac{K_{inv} \cdot (\tau + i)}{Z_h \cdot f}, \quad (1)$$

in which

K_{inv} investment costs of fuel cell set per kW of power installed,

τ amortization factor (reciprocal service life in years),

i interest factor equals $p/100$; p = rate of interest in % (in computations of economy it is sometimes customary to deal only with half the replacement costs in connection with interest; this is of minor importance for our comparative treatment),

Z_h number of operating hours per year,

f load factor = $\frac{\text{produced power}}{\text{installed power}}$.

By installed power we mean the maximum power derivable from the set. The maximum power density (mW/cm^2) corresponding to this power has been used by us as the basis for our computational examples 2.1 to 2.5.

1.2. Operating and Maintenance Costs K_B

The load factor and the number of operating hours per year must also be considered in transferring personnel costs to the energy price, just like capital service. According to this we get

$$K_B = \frac{k}{N_{in} \cdot f \cdot h} \tag{2}$$

with

k hourly operating costs for the installed power,

N_{in} installed power in kW

h operating time factor = $Z_h/8760$.

A fuel cell set with reforming[2] without additional devices for purifying the cracked gases requires only slight maintenance which occurs in cycles, and this does not amount to more than an average of 1 to 2 minutes per day for a battery with 1 kW power. For an assumed hourly rate of 10 DM this corresponds to $10/24 \cdot 60 = 0.007$ to $2 \cdot 10/24 \cdot 60 = 0.014$ DM hourly operating costs, i.e., an average of 0.01 DM/kW. They increase if the load factor and the operating

[2]Reforming means vapor cracking of hydrocarbons (thermal treatment with water vapor at 600 to 800°C — German: Konvertierung).

time factor become less than 1 and the installation requires a higher maintenance and repair expenditure.

1.3. Energy Transformation Costs K_u

In computing the energy transformation costs the reaction at the base of the energy transformation must first be considered in connection with all of the parameters affecting its efficiency, and the total efficiency is to be determined by computation or experimentally.

Under some conditions a very complex system of partial processes with a single numerical factor is to be adopted here. For example, such a system comes to the fore if a fuel with water vapor is converted in the energy transformation, then the cracked gas obtained is purified and is to be converted with alkali electrolytes in a fuel cell. Here several kinds of efficiency are to be considered, and all auxiliary materials for reforming and purifying must enter the calculations along with the fuel costs.

Therefore the following is valid for the energy trasnformation costs:

$$K_u = \frac{K_{st} \cdot 860}{H_u \cdot \eta_f}. \qquad (3)$$

Here:

K_{st} fuel costs per kg (or m^3) of fuel,

860 rounded electrocaloric transformation factor (1 kWh = $859.845 \cdot 10^3$ cal),

H_u lower calorific value of the fuel in kcal/kg (or kcal/m^3),

η_f total efficiency of the fuel cell set with a load factor f.

The efficiency of the fuel cells dependent on the load factor f must be determined by measurements on the corresponding cells. For load factors of 0.1 to 1.0 the values usually lie between 0.7 and 0.25 without reforming. Since in practice reforming seldom exceeds an efficiency of 0.7, the total efficiency of the fuel cell set is reduced to values between 0.5 and 0.15. As our own /143 research and as data from the literature show, the differences between various kinds of fuel cells are not so great that they have a decisive effect upon the energy production costs. In Table 1 the degrees of efficiency are summarized as a function of the load factor as they correspond to the current state of technology. The data for the tungsten carbide-carbon fuel cell originate in our own measurements.

TABLE 1. EFFICIENCY η_f OF VARIOUS KINDS OF CELLS AS A FUNCTION OF LOAD FACTOR f.

	With acid electrolytes				With alkali electrolytes	
Load factor f	WC/C with H_2	WC/C with converter	Pt/Pt with H_2	Pt/Pt with converter	Ni/Ag with NH_3 cracker	Ni/Ag with very pure gases or hydrazine
0.1	0.56	0.39	0.59	0.41	0.55	0.69
0.2	0.53	0.37	0.55	0.38	0.52	0.65
0.3	0.50	0.35	0.52	0.36	0.49	0.61
0.4	0.48	0.33	0.49	0.34	0.46	0.58
0.5	0.45	0.32	0.46	0.32	0.44	0.55
0.6	0.42	0.29	0.43	0.30	0.42	0.53
0.7	0.38	0.27	0.40	0.28	0.40	0.50
0.8	0.34	0.24	0.37	0.26	0.37	0.46
0.9	0.29	0.20	0.33	0.23	0.32	0.40
1.0	0.22	0.16	0.27	0.19	0.24	0.30

Thus for fuel cells we get as the energy production cost P in DM/kWh

$$\begin{aligned} P &= K_K + K_B + K_U \quad (\mathrm{DM/kWh}) \\ &= \frac{K_{inv} \cdot (\tau + i)}{Z_h \cdot f} + \frac{k}{N_{in} \cdot f \cdot h} + \frac{K_{St} \cdot 860}{H_u \cdot \eta_f} \quad (\mathrm{DM/kWh})\,. \end{aligned} \tag{4}$$

As a variation of equation (3) we get, for the energy transformation in secondary batteries (accumulators),

$$K_U = \frac{k_{el}}{\eta_{el}}, \tag{5}$$

where

k_{el} is the price of the kWh for the charging process,

η_{el} total efficiency of the charging process including transformer and rectifier.

The computation of K_K and K_B takes place here as in fuel cells.

2. Comparison of the Energy Production Cost of Different Kinds of Fuel Cells

The many kinds of restrictive magnitudes which enter into the energy production costs have varied importance in the different kinds of fuel cells. Therefore it is not very logical to wish to fix one sufficiently comparable working point between the cells to be compared by corresponding introduction of certain operating conditions in them and thus to examine the comparisons with only one numerical reference per type of cell. Under certain conditions this can lead to false judgement. It seems much more appropriate to compute the energy costs in a dynamic way (as a factor of unified variable parameters, e.g., operating hours per year, service life or load factor) and to study the characteristics of the different cells. Here we shall use the relationship between energy costs and load factor, because the dependence of the costs on the load factor seems to be particularly appropriate for comparing energy production costs, since in fuel cells the density affects the efficiency and the power specifically. This method of representation is clear and illustrates the characteristic differences among the kinds of low temperature fuel cells treated. The comparative judgement of the following examples is to be found in Section 3.

The cells have the following varying characteristics:

- cheap cells-cheap fuel (2.1 and 2.2)
- expensive cells-cheap fuel (2.3)
- cheap cells-expensive fuel (2.4 a, b and 2.5).

It should be pointed out in connection with the computational examples that data based on assumptions must be used along with the data corresponding to the state of technology. Therefore the following examples are to be considered an attempt to compare different kinds of cells in which we have striven to form comparable assumptions for all kinds of fuel cells. The 3 places given in the tables after the decimal point result from the fact that very small orders of magnitude must often be considered in cost components.

2.1. Tungsten Carbide-Carbon Fuel Cells with a Gasoline Reformer

We made these computations on the basis of the following data:

α (specific power)	50 mW/cm^2
K_{inv} (investment costs per kW)	1,200 DM/kW incl. reformer

τ (amortization factor)	0.2 (corresponding to 5 years of service life
i (interest factor)	0.1
Z_h (hours of operation per year)	8,000
k (hourly operating cost)	0.01 DM/kW
K_{ST} (fuel costs (untaxed gasoline))	0.15 DM/kg
H_u (caloric value)	10,000 kcal/kg
η_f (efficiency)	see Table 1, column 3

From this the individual costs are computed:

$$
\begin{aligned}
K_K &= \frac{K_{inv} \cdot (\tau + i)}{Z_h \cdot f} = \frac{1200 \cdot (0{,}2 + 0{,}1)}{8000 \cdot f} \\
K_B &= \frac{k}{N_{in} \cdot f \cdot h} = \frac{0{,}01}{1 \cdot f \cdot 0{,}9} \\
K_U &= \frac{K_{St} \cdot 860}{H_u \cdot \eta_f} = \frac{0{,}15 \cdot 860}{10\,000 \cdot \eta_f}
\end{aligned}
\tag{6}
$$

The corresponding values are presented in Table 2, especially for η_f.

TABLE 2. ENERGY PRODUCTION COSTS AS A FUNCTION OF LOAD FACTOR IN A WC/C FUEL CELL BATTERY WITH REFORMING (SEE FIGURES 1 AND 4).

f	η_f	K_K DM/kWh	K_B DM/kWh	K_U DM/kWh	P (2.1) DM/kWh
0,1	0,39	0,45	0,11	0,033	0,593
0,2	0,37	0,225	0,055	0,035	0,315
0,3	0,35	0,150	0,037	0,037	0,224
0,4	0,33	0,113	0,028	0,039	0,180
0,5	0,32	0,090	0,022	0,041	0,153
0,6	0,29	0,075	0,018	0,044	0,137
0,7	0,27	0,064	0,016	0,048	0,128
0,8	0,24	0,056	0,014	0,054	0,124
0,9	0,20	0,050	0,012	0,065	0,127
1,0	0,16	0,045	0,011	0,080	0,136

Commas indicate decimal points.

The most economic working point lies at a load factor 0.8 with energy production costs of 0.12 DM/kWh. The slope of the curves of the individual cost components is represented in Figure 1. The broad optimum (f = 0.6 to 1.0) is of interest.

2.2. Tungsten Carbide-Carbon Fuel Cell with Methanol Cracker /144

The combination of the WC/C cell with a methanol cracker presents an alternative to Section 2.1. In catalytic methanol cracking, the preparation of water vapor for the cracking process is omitted ($CH_3OH \rightarrow CO + 2H_2$), and the cracking takes place at considerably lower temperatures than vapor cracking, namely at about 300°C. On the other hand fuel costs are somewhat higher. In our computation we use 0.30 DM/liter of methanol corresponding to 0.38 DM/kg and a caloric value H_u = 4,660 kcal/kg. For the sake of simplicity we accepted other data as in 2.1, since the difference is not decisive.

The optimum load factor here is 0.6 with 0.33 DM/kWh energy production costs. The energy production costs of the fuel cells treated here are shown in Figures 1 and 4.

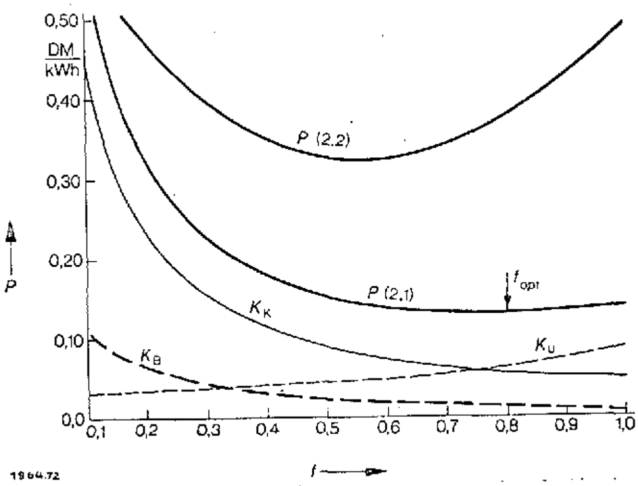

Figure 1. Energy Production Costs P(2.1) of a Tungsten Carbide-Carbon Fuel Cell with a Gasoline Reformer As A Function of Load Factor f (See Table 2). (P(2.2) for an identical cell with a methanol cracker), f_{opt} optimal load factor, other designations according to equations (1) to (4).

2.3. Platinum-Platinum Fuel Cell with Gasoline Reformer

In the American TARGET Program and in several military development laboratories in the USA acid electrolytes and platinum electrodes are worked with. The energy costs here are determined in the first place by charging the electrodes with catalysts and by the catalyst price.

α (specific power)	200 mW/cm^2
K_{inv} (investment costs per kW)	7,500 DM/kW incl. reforming and purifying the gas
τ (amortization factor)	0.333 (corresponding to 3 years service life
i (interest factor)	0.1
Z_h (operating hours per year)	8,000
k (hourly operating costs)	0.02 DM/kW
K_{st} (fuel costs (untaxed gasoline))	0.15 DM/kg
H_u (caloric value)	10,000 kcal/kg
η_f (efficiency)	see Table 1, column 5

The most favorable working point lies at a load factor 1 with about 0.50 DM/kWh energy production costs. The cost curves are presented in Figure 2. The energy production costs here are determined by the financial expenditure of K_K.

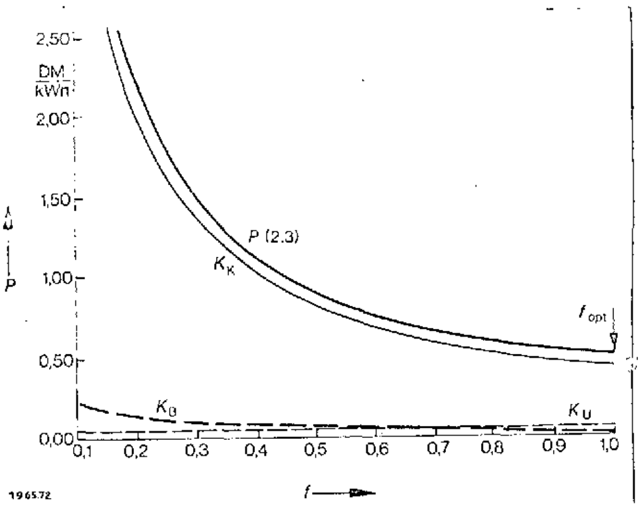

Figure 2. Energy Production Costs P (2.3) of a Platinum-Platinum Fuel Cell with a Gasoline Reformer As a Function of Load Factor f (See Table 4). Designations of the curves as in Figure 1.

2.4. Nickel-Silver Fuel Cell

Low temperature fuel cells with alkali electrolytes are the most developed. Several remarkably developed batteries of 1 to 5 kW power are known; they are operated with very pure gases. Therefore it would be interesting to compare the fuel cells described above with an alkali battery with a gasoline reformer. Unfortunately we have not learned of any set driven in this way with a service life of more than 100 hours. Neither do we have any data available about the range and costs of a gasoline reformer with a sufficient purification device to prepare fuel gas free of carbon dioxide. Nor is there any data about purifying air from the ubiquitous carbon dioxide. It seems doubtful that such devices could be driven in an economically defensible way, since even small amounts of carbon dioxide in hydrogen and oxygen in the pores of the electrodes lead to a precipitation of potassium bicarbonate and thus to an irreversible alteration of the electrode processes [10, 11].

Therefore in the following we have computed the hydrogen operation from an ammonia cracker and operation with gases from tanks:

Nickel-Silver Fuel Cell with Alkali Electrolytes and with Cracked Hydrogen

α (specific power)	320 mW/cm^2
K_{inv} (investment costs)	1,000 DM/kW incl. ammonia cracking device
τ (amortization factor)	0.2 (corresponding to 5 years of service life

i (interest factor)	0.1
Z_h (operating hours per year)	8,000
k (hourly operating costs)	0.01 DM/kW
K_{st} (fuel costs, basis)	technical ammonia 1.40 DM/kg, whence computed: 0.713 DM/m^3 H_2; oxygen from steel tanks: 3.05 DM/m^3 corresponding to 2.238 DM/m^3 of H_2 to be converted
H_u (caloric value)	2,570 kcal/m^3
η_f (efficiency)	See Table 1, column 6

The lowest energy costs lie at a load factor 0.2 with 1.69 DM/kWh. See Figure 4 with comparison with other fuel cells.

Nickel-Silver Fuel Cell with Alkali Electrolytes Driven with Pure Gases From Tanks

α (specific power)	320 mW/cm^2	
K_{inv} (investment costs)	800 DM/kW	
τ (amortization factor)	0.2 (corresponding to 5 years of service life)	
i (interest factor)	0.1	
Z_h (operating hours per year)	8,000	
k (hourly operating costs)	0.01 DM/kW	
K_{st} (fuel costs)		
Hydrogen:	2.80 DM/m^3	4.30 DM/m^3 of H_2 to be converted
Oxygen:	3.05 DM/m^3	
H_u (caloric value)	2,570 kcal/m^3	
η_f (efficiency)	see Table 1, column 7	

The minimum energy production costs lie at a load factor 0.2 with about 2.50 DM/kWh. The curves of the individual cost components are presented in Figure 3. Here the energy production costs are determined by K_u, i.e., from the fuel costs.

2.5. Nickel-Silver Fuel Cell for Hydrazine-Hydrogen Peroxide

Hydrazine is supposed to be a very suitable fuel for low temperature fuel cells. However, not only the high price, but also its toxicity [12], oppose /146 its use. We used hydrogen peroxide as an oxidation material since the same difficulties occur with atmospheric oxygen as in other alkali cells with carbon dioxide.

α (specific power)	300 mW/cm^2
K_{inv} (investment costs)	1,200 DM/kW
τ (amortization factor)	0.2 (corresponding to 5 years service life)
i (interest factor)	0.1
Z_h (operating hours per year)	8,000
K (hourly operating costs)	0.01 DM/kW
K_{st} (fuel costs (untaxed hydrazine))	6 DM/kg, including hydrogen peroxide: 13.50 DM/kg hydrazine to be converted
H_u (caloric value)	3,600 kcal/kg
η_f (efficiency)	See Table 1, column 7

Because of the high operating material costs the optimum load factor lies below 0.1; in the f area in the tables the price of kWh begins to rise with the load factor right from a small charge.

3. Conclusions from the Comparison of the Different Fuel Cells

In our computations the investment costs assumed for the fuel cell set could represent the most uncertain factor, since they depend not only on the technical development but also on the number of pieces manufactured. However, since we began with equalized assumptions for all of the types of fuel cells treated, the results obtained stand on a comparable basis, and possible mistakes in the assumptions would not essentially change the ratio of the data for the individual kinds of fuel cells. The possible effect of the amount of investment costs assumed in the price of energy production will be treated in a later work [6].

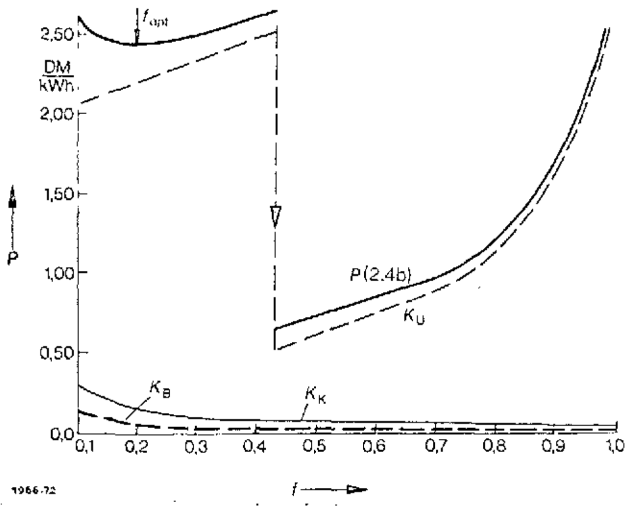

Figure 3. Energy Production Costs P (2.4b) of a Nickel-Silver Fuel Cell for Pure Hydrogen and Oxygen As a Function of Load Factor f (See Table 6). Designations of the curves as in Figure 1. For reasons of technical design the curve was shifted downward by 2.00 DM beginning with f = 0.43. Abf = 0.4 ist replaced below by 2.00 D.M. bZ-tB means "cheap cells — expensive fuel", etc.

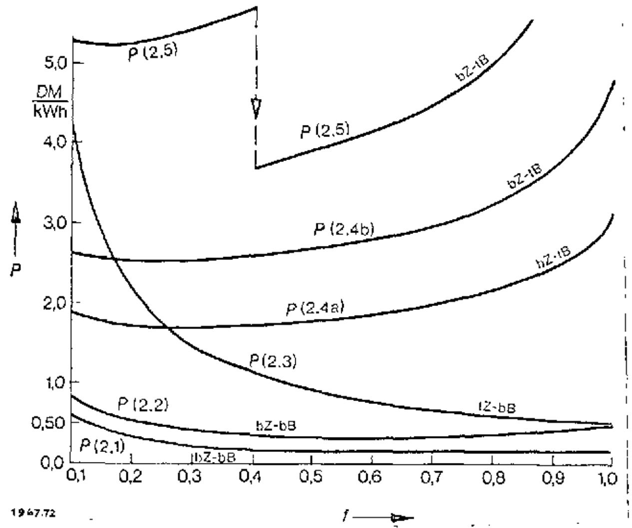

Figure 4. Comparison of the Energy Production Costs of all Examples 2.1 to 2.5 of Low Temperature Fuel Cells As a Function of Load Factor f (Fuel Cells 2.1 to 2.3 With Acid Electrolytes and 2.4-2.5 With Alkali Electrolytes). Examples 2.1, 2.3, 2.4b see Figures 1 to 3. Examples 2.2, 2.4a, 2.5 see Tables 3, 5 and 7.

TABLE 3. ENERGY PRODUCTION COSTS AS A FUNCTION OF LOAD FACTOR IN A WC/C FUEL CELL BATTERY WITH A METHANOL CRACKER (SEE FIGURES 1 AND 4).

f	η_f	K_K DM/kWh	K_B DM/kWh	K_U DM/kWh	P (2.2) DM/kWh
0,1	0,39	0,45	0,11	0,179	0,739
0,2	0,37	0,225	0,055	0,189	0,469
0,3	0,35	0,150	0,037	0,200	0,387
0,4	0,33	0,113	0,028	0,212	0,353
0,5	0,32	0,090	0,022	0,222	0,334
0,6	0,29	0,075	0,018	0,238	0,331
0,7	0,27	0,064	0,016	0,259	0,339
0,8	0,24	0,056	0,014	0,310	0,380
0,9	0,20	0,050	0,012	0,35	0,412
1,0	0,16	0,045	0,011	0,438	0,494

Commas indicate decimal points

TABLE 4. ENERGY PRODUCTION COSTS AS A FUNCTION OF LOAD FACTOR IN A Pt/Pt FUEL CELL BATTERY WITH ACID ELECTROLYTE, GASOLINE REFORMING AND CRACKED GAS PURIFICATION (SEE FIGURES 2 AND 4).

f	η_f	K_K DM/kWh	K_B DM/kWh	K_U DM/kWh	P (2.3) DM/kWh
0,1	0,41	4,06	0,22	0,032	4,312
0,2	0,38	2,03	0,11	0,034	2,174
0,3	0,36	1,353	0,073	0,035	1,451
0,4	0,34	1,015	0,055	0,038	1,108
0,5	0,32	0,812	0,044	0,041	0,897
0,6	0,30	0,677	0,037	0,043	0,757
0,7	0,28	0,580	0,031	0,046	0,657
0,8	0,26	0,508	0,028	0,050	0,586
0,9	0,23	0,451	0,024	0,057	0,532
1,0	0,19	0,406	0,022	0,068	0,496

Commas indicate decimal points.

TABLE 5. ENERGY PRODUCTION COSTS AS A FUNCTION OF LOAD FACTOR IN A Ni/Ag FUEL CELL WITH AN ALKALI ELECTROLYTE AND OPERATION WITH HYDROGEN FROM AMMONIA AND OXYGEN FROM STEEL TANKS (SEE FIGURE 4).

f	η_f	K_K DM/kWh	K_B DM/kWh	K_U DM/kWh	P (2.4 a) DM/kWh
0,1	0,55	0,38	0,11	1,362	1,852
0,2	0,52	0,19	0,055	1,440	1,685
0,3	0,49	0,127	0,037	1,535	1,699
0,4	0,46	0,095	0,028	1,614	1,737
0,5	0,44	0,076	0,022	1,702	1,800
0,6	0,42	0,063	0,018	1,767	1,848
0,7	0,40	0,054	0,016	1,873	1,943
0,8	0,37	0,048	0,014	2,035	2,097
0,9	0,32	0,042	0,012	2,341	2,395
1,0	0,24	0,038	0,011	3,121	3,170

Commas indicate decimal points.

TABLE 6. ENERGY PRODUCTION COSTS AS A FUNCTION OF LOAD FACTOR IN A Ni/Ag FUEL CELL WITH AN ALKALI ELECTROLYTE AND OPERATED WITH PURE GASES FROM TANKS (SEE FIGURE 3).

f	η_f	K_K DM/kWh	K_B DM/kWh	K_U DM/kWh	P (2.4 b) DM/kWh
0,1	0,69	0,45	0,11	2,086	2,646
0,2	0,65	0,225	0,055	2,214	2,494
0,3	0,61	0,150	0,037	2,357	2,546
0,4	0,58	0,113	0,028	2,481	2,622
0,5	0,55	0,090	0,022	2,616	2,728
0,6	0,53	0,075	0,018	2,715	2,808
0,7	0,50	0,064	0,016	2,878	2,958
0,8	0,46	0,056	0,014	3,128	3,198
0,9	0,40	0,050	0,012	3,598	3,660
1,0	0,30	0,045	0,011	4,797	4,853

Commas indicate decimal points.

TABLE 7. ENERGY PRODUCTION COSTS AS A FUNCTION OF LOAD FACOTR IN A Ni/Ag FUEL CELL BATTERY FOR HYDRAZINE--HYDROGEN PEROXIDE (SEE FIGURE 4).

f	η_f	K_K DM/kWh	K_B DM/kWh	K_U DM/kWh	P (2.5) DM/kWh
0,1	0,69	0,45	0,11	4,674	5,234
0,2	0,65	0,225	0,055	4,962	5,242
0,3	0,61	0,150	0,037	5,287	5,474
0,4	0,58	0,113	0,028	5,560	5,701
0,5	0,56	0,090	0,022	5,759	5,871
0,6	0,53	0,075	0,018	6,085	6,178
0,7	0,50	0,064	0,016	6,450	6,530
0,8	0,46	0,056	0,014	7,011	7,081
0,9	0,40	0,050	0,012	8,063	8,125
1,0	0,30	0,045	0,011	10,750	10,806

Commas indicate decimal points.

Figure 4 reflects the cost curves P for the energy production of the fuel cells treated in Sections 2.1 to 2.5. As Figure 4 shows, high fuel costs have an essentially worse effect on economy than do high investment costs, since the optimum load factor with a cheap fuel lies near 1, i.e., at maximum power, while it shifts to lower power with increasing fuel costs. Above the load factor 0.5, the superiority of cells with acid electrolytes in comparison to those with alkali electrolytes in respect to energy production costs is very convincing, even with the high investment costs of the Pt/Pt cell (see Section 2.3). The computations also demonstrate the fact that the WC/C cell is more economic than other low temperature fuel cells in spite of its essentially smaller specific power and its low efficiency.

REFERENCES

1. Ostwald, W., "Scientific Electrochemistry in the Present and the Technical Future," *Z. Elektrochem.*, Vol. 1, pp. 122-125, 1894.
2. Bacon, F. T., "The High Pressure Hydrogen-Oxygen Fuel Cell," *Fuel Cells*, editor G. Young, Reinhold Publ. Corp., New York, pp. 51-66, 1960.
3. Anonymous, "Power Supply in Apollo XI," *Chem. Ing. Techn.*, Vol. 41, pp. 1085-1088, 1969.
4. Justi, E. W. and A. W. Winsel, *Kalte Verbrennung* [Code Combustion], Franz Steiber-Verlag, GmbH., Wiesbaden, p. 60, 1962.
5. Boehm, H. and F. A. Pohl, "Tungsten Carbide, An Electrocatalyst for Fuel Cells," *Wiss. Ber. AEG.-TELEFUNKEN*, Vol. 41, No. 2, pp. 46-49, 1968.
6. Boehm, H., H. Carl and F. A. Pohl, "The Economic Applicability of Tungsten Carbide-Carbon Fuel Cells," *Wiss. Ber. AEG.-TELEFUNKEN*, Vol. 46, No. 3, 1973, to appear shortly.
7. Berger, Carl, editor, *Handbook of Fuel Cell Technology*, Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1968.
8. Clow, C. G., "Some Basic Economics of Alkaline Fuel Cells," Report of the 2nd Internal Meeting for the Study of Fuel Cells, pp. 89-93, Brussel, 1967.
9. Gabler, Dr., *Wirtschafts-Lexikon* [Economic Lexicon], 7th edition, Verlag, Dr. Th. Gabler, Wiesbaden, 1967.
10. Vic, R. and A. M. Grehier, "CIPEL, Study of the Conditions of Forming Carbonates in Alkaline Electrolytes," Report of the 2nd Internal Meeting for the Study of Fuel Cells," pp. 201-205, Brussel, 1967.
11. Cnobloch, H., H. Nischik and F. V. Sturn, "Hydrogen-Oxygen Fuel Cells for Low Maintenance Operation," *Chem. Ing. Techn.*, Vol. 41, pp. 146-154, 1969.
12. "MAK-Value List," *Deutsche Forschungshemeinschaft, ZH*, Vol. 1/410, H. Heymann-Verlag, 1971.

Translated for the National Aeronautics and Space Administration under Contract No. NASw-2485 by Techtran Corporation, P.O. Box 729, Glen Burnie, Maryland, 21061; translator, Lawrence W. Murphy, Ph.D.